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THE NORTH AMERICAN HIGH-LEVEL ANTICYCLONE

By THOMAS R. REED

[Weather Bureau, San Francisco, Calif., November 1933]

The existence of an anticyclonic system of air circulation at high levels over the southwestern portion of the North American Continent during the warm season is one of the most interesting and important revelations yielded by aerological investigations in the United States. Prior to these investigations such a thing was unsuspected, at least in the form in which it is now regularly observed, although ample theoretical grounds existed for assuming that it was there. Since the inauguration of daily pilot-balloon runs in the Far Western States, however, information has accumulated about this high-level anticyclone until today forecasters in the Far West look upon it as one of the distinctive and influential meteorological features of their domain.

Before 1921, when the first regular pilot-balloon work was undertaken on the Pacific coast, it was commonly supposed that a sort of monsoonal wind circulation existed over California and the neighboring ocean in summer. The observed westerly winds from the sea were supposed to be warmed over the land, to rise and return to sea at higher levels. In other words, a west wind at the surface presupposed a return east wind aloft. This assumption was considered sound enough at one time to incorporate in a manual of instructions for Marine Observers, but balloon runs which were begun in San Francisco in 1921 failed signally to reveal east winds aloft except on rare occasions; rather they showed the upper winds to be usually from some southerly quarter in summer. Since moving air (in the Northern Hamisphere) has high pressure on its right the problem was presented of a barometric gradient at high levels *sloping upward over the Nevada Plateau*, a region where low pressure is a normal summer condition at the surface of the earth.

It was not until some years later, not, in fact, until a wide network of upper-air stations had been installed in the southwestern United States in connection with the elaborate airways weather service begun by the Government in 1928, that this phenomenon and its cause were fully evident. Then sufficient free-air data soon became available for plotting the wind circulation at high levels daily throughout a large part of the Pacific Southwest, and from these plots the habitual anticyclonic or clockwise circulation at high levels became clearly evident. Winds aloft over southern New Mexico and southern Arizona often were observed to be from the east; over southern California from the south or southeast; over northern California from the south or southwest, and over northern portions of the Great Basin from the west or northwest. Noting this situation one day, when the condition was extremely obvious, my colleague, Maj. E. H. Bowie, epitomized it as "a perfect example of Ferrel's high-level anticyclone". Certainly Ferrel has described it, but equally certainly he never expected to see his description vindicated in such a way. Reference to his "Popular Treatise on Winds" (pp. 258–261) will make this clear. Both his text and diagram presuppose an anticyclonic circulation superposed on a cyclonic: Outflowing clockwise winds aloft over inflowing counterclockwise winds below. In the lower levels the isobarometric surfaces were assumed to be concave, in the upper levels, convex.

While such conditions have not been found in dynamically-caused depressions, for reasons which are now familiar to everyone, they are characteristic of the thermally induced depression of the summer season over the southwestern United States. Particularly is this true of the convexity of the upper isobarometric surfaces and of the uniformity of the attendant clockwise circulation around them. In 1928 when this regime of wind and pressure first became apparent, it was brought before the meeting of the American Meteorological Society at Claremont, Calif., by Bowie, where it aroused considerable interest and was briefly discussed. A year later he referred to it in an article published in the MONTHLY WEATHER REVIEW,[1] wherein he explained the nature and cause of the reversed gradient aloft, using two California stations for illustration, one located in the hot interior and the other on the coast. In the following year (1930) still more aerological stations were addea to the observational net and the results of the daily pilot-balloon runs were made universally available by publication regularly in the MONTHLY WEATHER REVIEW of "resultant" upper-wind data for the entire United States. By means of these data it became possible to plot resultant winds for monthly periods over a very large area and for a number of different levels from the surface up to 5,000 m altitude, and the consequence of such charting has been to still further elucidate the anticyclonic regime aloft ana to understand better its nature and effects. The salient features thus revealed, considered topically, are as follows:

Period.—The anticyclone, being distinctly a warm-season phenomenon, makes its first appearance in the spring, but it does not become fully established until midsummer. It reaches its maximum development in July and August, and disappears, except for sporadic recurrences, in October.

Height.—This is a variable factor and is dependent in some degree on the height and configuration of the land masses beneath. The anticyclonic circulation is not apparent as a whole below the 10,000-foot level (above mean sea level) since the disturbing element of mountain peaks and ridges thereunder prevents conformity to the gradient wind ideal. It is developed almost without hindrance at

[1] MONTHLY WEATHER REVIEW, 1929, vol. 57, pp. 332–334.

the 14,000-foot level. No free-air observations are available between that height and 20,000 feet, but charts drawn for the 20,000-foot level (the maximum height for which the balloon runs are reported) show its existance there and imply that it extends upward as far as the tropopause.

Location.—(Charts 1 to 12.) The controlling factors being surface temperature and a latitudinal position somewhere between the northeast trades and the westerlies of higher latitudes, the anticyclone is necessarily confined to the southern United States and northern Mexico, but within these limits it is quite mobile and its crest moves through a very considerable range of latitude and longitude. With only 3 years' observations to draw upon, it would be premature to assume a mean position, but from study of the available resultant wind data it seems reasonable to suppose that in normal years the crest often will be found over or east of the southern Rocky Mountains; that is to say, over Texas or New Mexico. However, this surmise applies only to the months when it is at its height, viz, July and August. It is ventured for the reason that July and August are preeminently the months of so-called "Arizona type" rains, and rains of this type are so evidently associated with the western quadrants of the anticyclone that they presuppose the position of its crest to be usually somewhere to the eastward in these months. Its mean monthly positions for the 3 seasons 1930–32, have been as follows: May, over northern Mexico; June, the same but encroaching on the southern border States; July, twice over the west Gulf States and once over Arizona; August, once over New Mexico, once over Arizona, and once over the west Gulf States; September, once over Arizona and twice over northern Mexico. References to its Mexican position are necessarily vague, as no upper-wind data are available from that country.

Relation to surface temperature.—It has been said that within limits its position is quite variable, the crest being sometimes west of the Continental Divide and sometimes east of it; sometimes north of the Mexican border and sometimes south of it. It appears first over Mexico and moves northward as the season advances, retreating to Mexico as the warm season wanes. The controlling factor, or at least a dominant influence, mean positions considered, seems to be surface temperature. Reference to individual months is of interest in this connection and bears out the inference. For example, during the memorably hot month of July 1930 (east of the Rockies), the mean position of the crest was over the west Gulf States, while in July 1931 when temperatures were considerably above normal over the far Southwest, its mean central position was over northern Arizona. Again in July and August 1932, with temperatures above normal in the Cotton Belt, the center was again over the west Gulf States, or thereabouts. Of unusual significance in this connection is the mean position of the anticyclone in September 1931. Temperatures in that month averaged as much as 8° F. above normal in the southern Plains States and Oklahoma, and so, notwithstanding the lateness of the season, an anticyclonic air circulation is plainly apparent on the wind-aloft chart over all the far Southwest, including Texas, Oklahoma, and Colorado. The crest of the anticyclone appeared to be over northwestern Mexico with the main axis pointing toward the northeast.

Effects.—The study of this anticyclone is of more than academic interest as it exerts a profound effect on the weather of the southwestern United States, and perhaps of an even greater area. It is associated with the remarkable atmospheric stability that gives California its characteristically dry summers, and with the atmospheric instability that is responsible for summer rains of the "Arizona type", a short distance eastward.

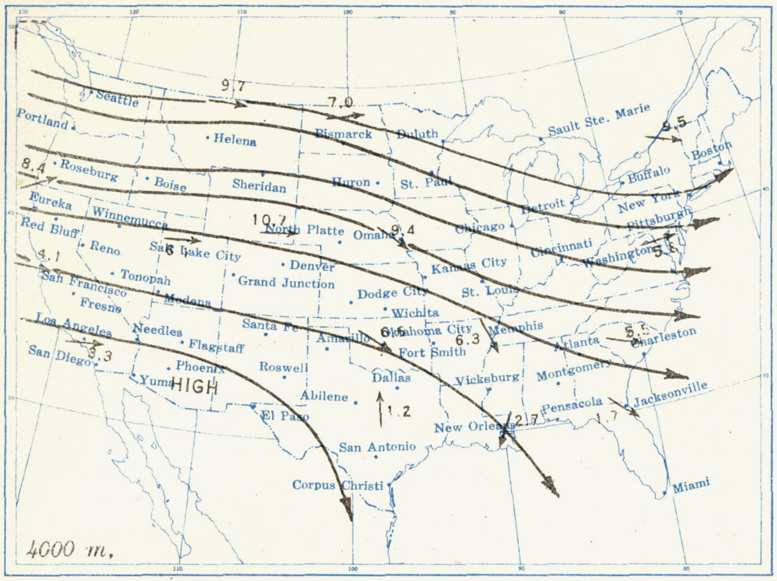
The first inquiry of the weather-minded newcomer to California is "Why no summer thunderstorms?" And the answer is: "The air is too warm aloft". Penetrative convection is only possible on rare occasions, notwithstanding that California surface temperatures must initiate as vigorous convection in the dry season as is to be found anywhere in the United States. But ascensional currents cannot be perpetuated to the point of condensation as they soon reach levels where air of higher temperature and hence of less density is encountered. This condition of stability is characteristic not alone of California in the warm season; but the rainless régime is subject to fewer interruptions in that State and Lower California than anywhere else. The reason for this stability, as has been said, is the warmth of the air aloft, and the source of this warm air is the high-level anticyclone around which it is circulating.[2]

If the same fountain does not send forth both sweet waters and bitter, we may ask with incredulity why the air circulating around the high-level anticyclone produces such opposite effects—stability on the one hand and instability on the other—"Arizona rains" on the east and California drought on the west. Looking at charts of summer-rainfall frequency percentages we are impressed by the marked preponderance of summer rains from central Arizona eastward, while to the westward their frequency falls off with conspicuous abruptness. In fact, the summer season is distinctly the wet season for one district and distinctly the dry season for the other. Alexander's thunderstorm chart[3] is even more impressive. For the 10-year period 1904–13, it shows a maximum (west of the 90th meridian) of 732 thunderstorm days at Santa Fe, N.Mex., which declines westward to less than 100 in California and a minimum of 10 at San Francisco. This situation is not peculiar to the southwestern United States only, but is integral with the climate of northern Mexico. In fact the rainfall "provinces" of northern Mexico fit exactly with our own rainfall provinces across the border and suggest that the explanation of one will satisfy the conditions of the other. We see that the region contiguous to southeastern Arizona and New Mexico is one of summer rainfall maxima, while immediately to the westward is found the California type, of almost rainless summers and the most extreme aridity in all Mexico. We cannot fail to remark that the dividing line between these two rainfall provinces is the mountain escarpment that fringes the western edge of the Mexican Plateau. This observation is most important because it suggests the explanation we are seeking (partial, at least) for the singular contrast in free-air temperatures over California on the one hand and over the Arizona "rainfall province" on the other.

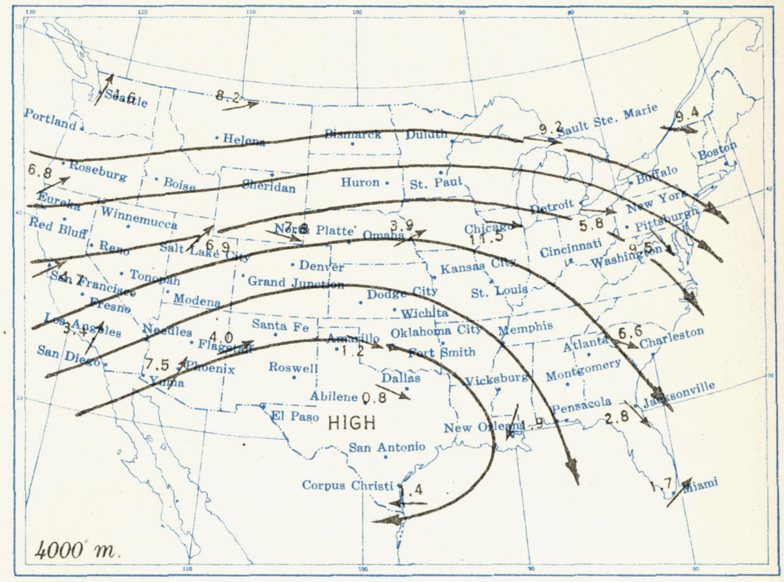
Let us suppose the high-level anticyclone to be centered, where it so often is in the summer, over Texas or New Mexico. This is the season of instability rains over the whole region to the east and south of it, i.e., from the Gulf States to southern Mexico, so we do not have to

[2] It is also true that California's rainless summers are attributable, in part, as Dr. Humphreys has pointed out in his "Physics of the Air" (1st edition), p. 302, to the fact that the temperature of the on-shore winds is too low and their humidity too small to permit penetrative convection, but this is only true because of the characteristic lapse rate over this region. Actually, there is much more water vapor present in California's atmosphere than in New Mexico's. At Santa Fe, N.Mex., with the greatest thunderstorm frequency of any place in the United States west of the 90th meridian, the mean absolute humidity (grs.) June, July, and August, is 2.94 at 8 a.m. and 2.62 at 8 p.m., while for California, with one tenth the thunderstorm frequency, the values are as follows: Sacramento, 4.18 and 5.31, respectively; Eureka, 4.14 and 4.27; San Francisco, 4.27 and 4.37; San Diego, 5.37 and 5.82. Yuma, Ariz., on the California line, in the hottest and most arid region on the continent, has a higher absolute humidity in summer than any station in New Mexico, and but little lower than many in Texas.

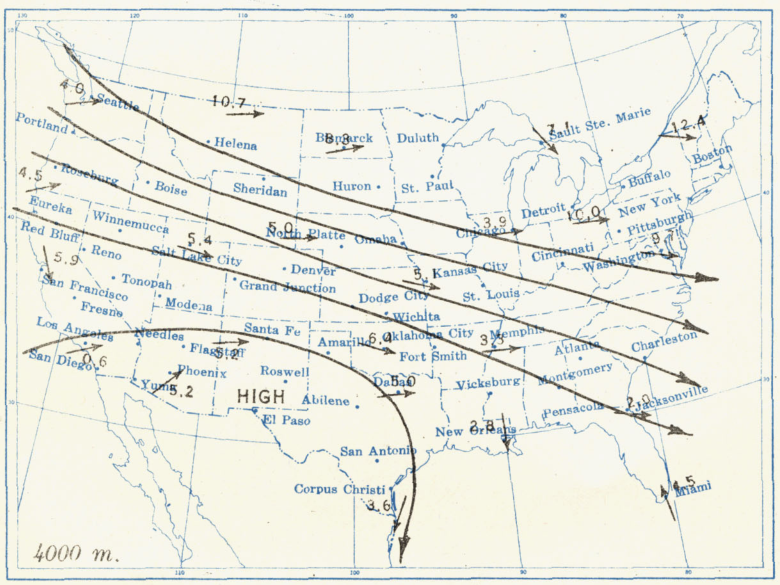
[3] MONTHLY WEATHER REVIEW, July 1915.



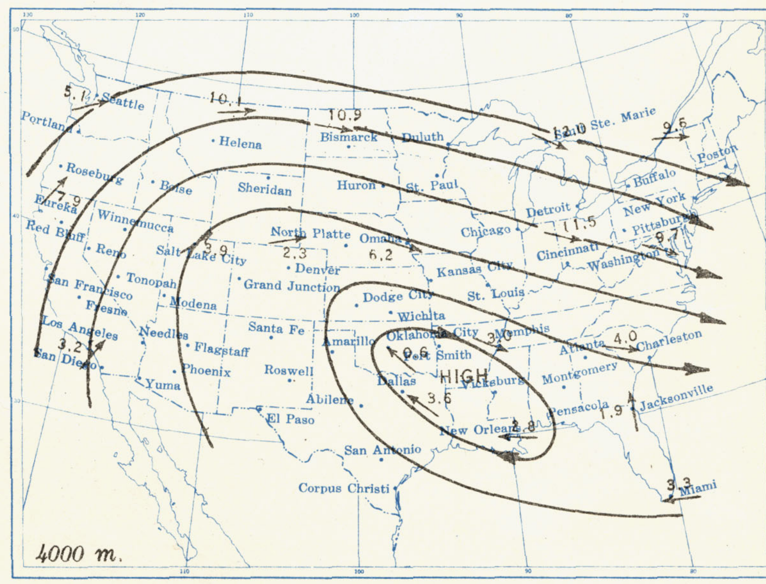
T. R. R.—1. June 1933.



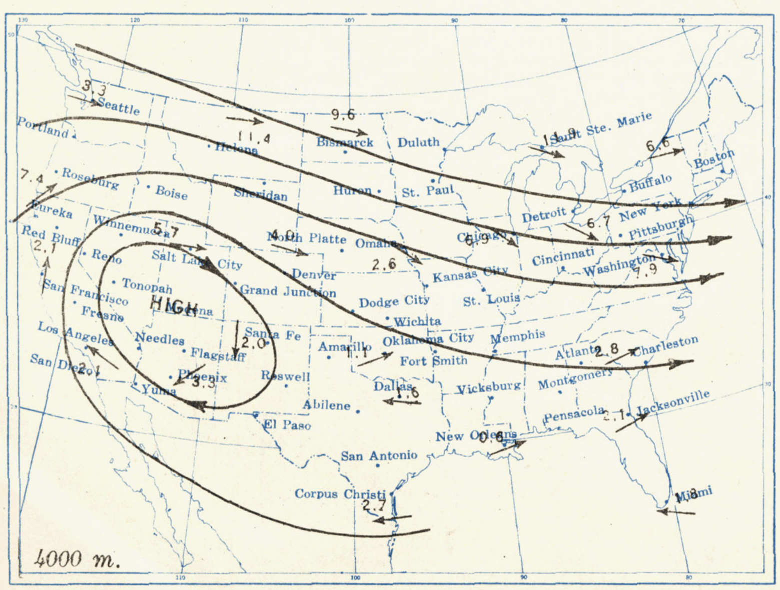
T. R. R.—2. June 1931.



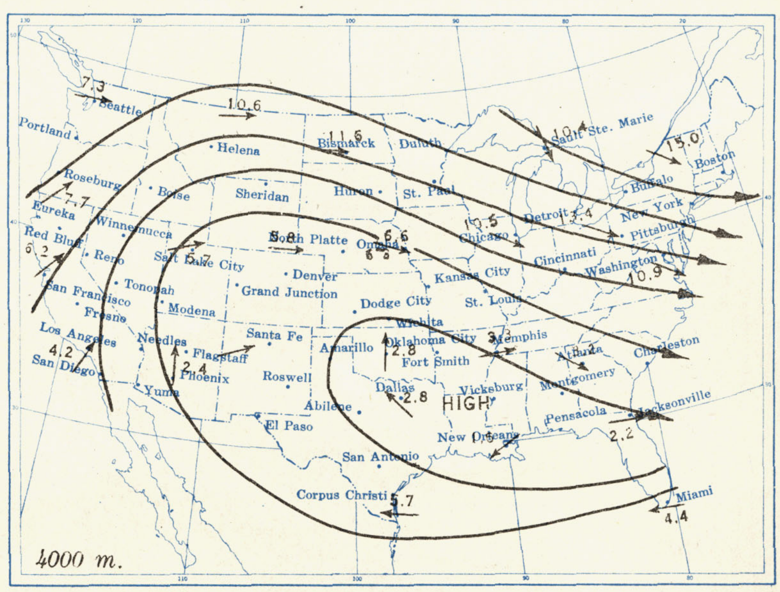
T. R. R.—3. June 1932.



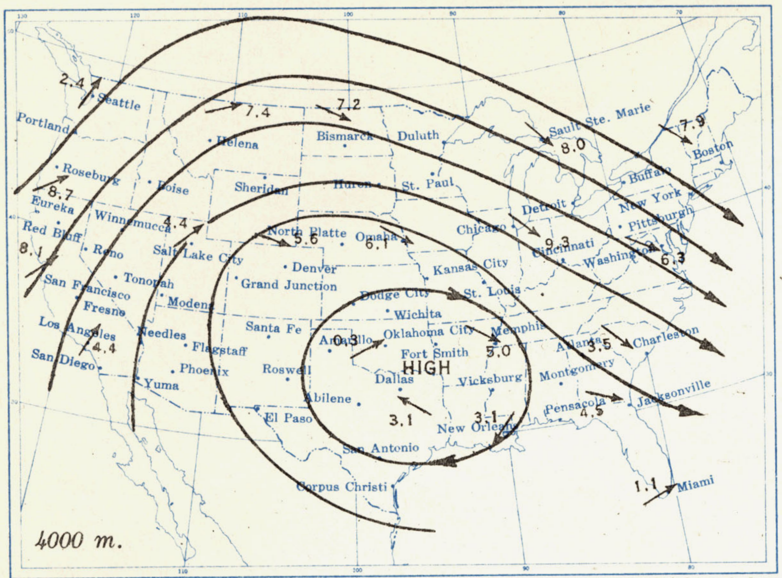
T. R. R.—4. July 1930. Temperatures averaged much above normal east of the Rockies, while west of them they were about normal. Hence the high-level anticyclone is centered over the Southern States east of the Continental Divide.



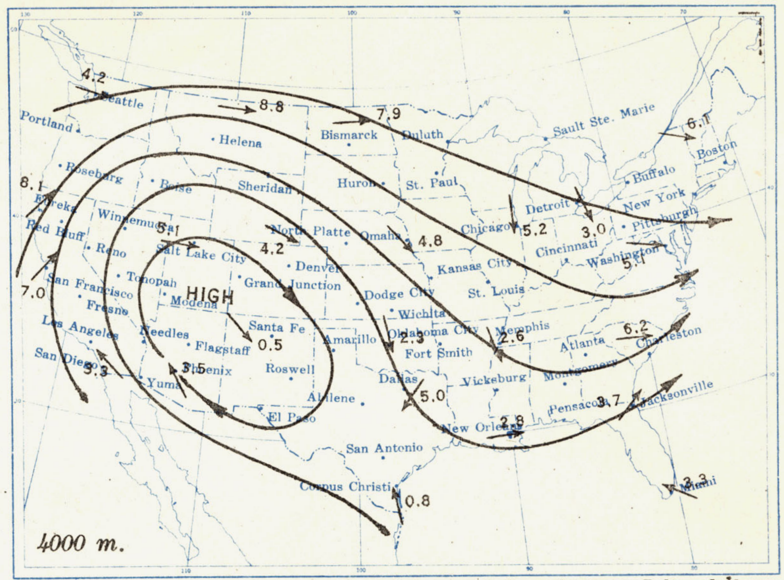
T. R. R.—5. July 1931. Temperatures near or above normal in Gulf States and much above normal over the far Southwest. Anticyclone centered west of the Continental Divide.



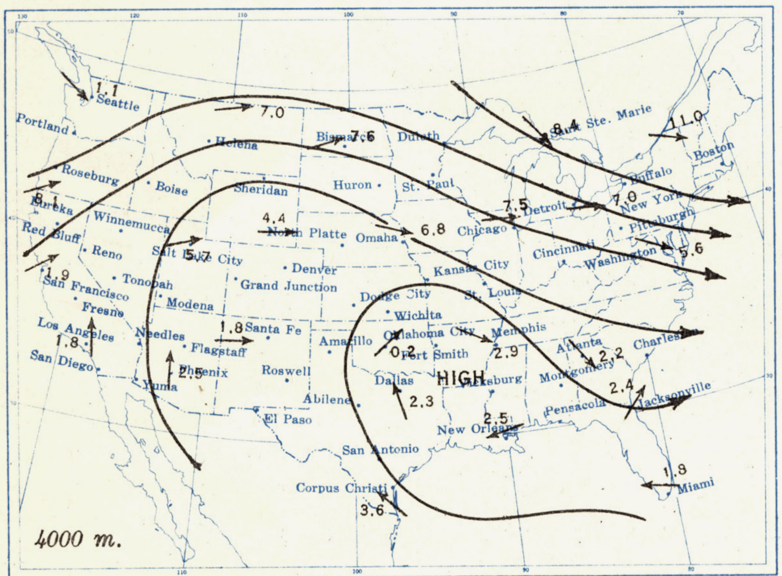
T. R. R.—6. July 1932. Temperatures well above normal in Middle West and South and below normal in California.



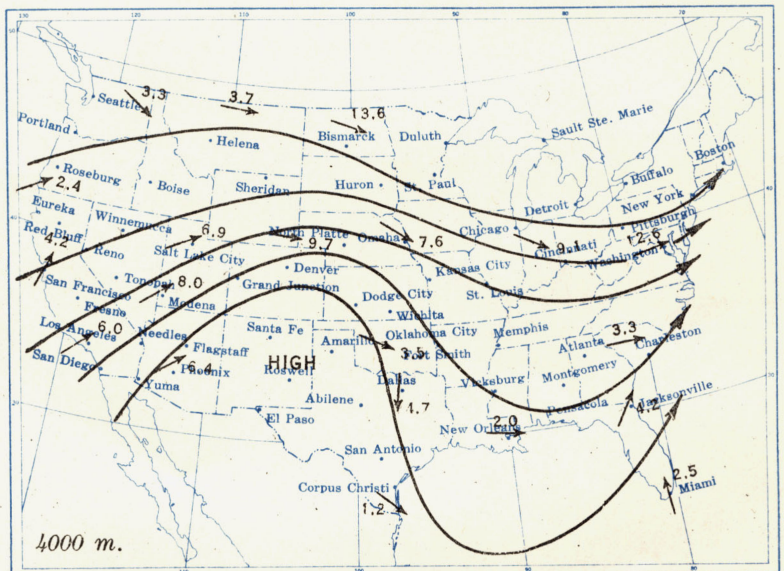
T. R. R.—7. August 1930. Temperatures above normal over and east of the Rockies; below normal to the westward.



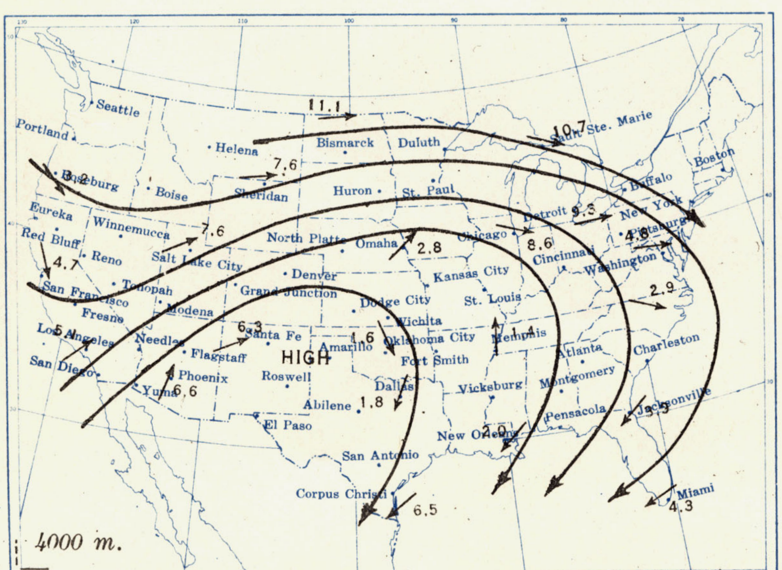
T. R. R.—8. August 1931. Temperatures below normal through Cotton Belt and above normal west of the Continental Divide.



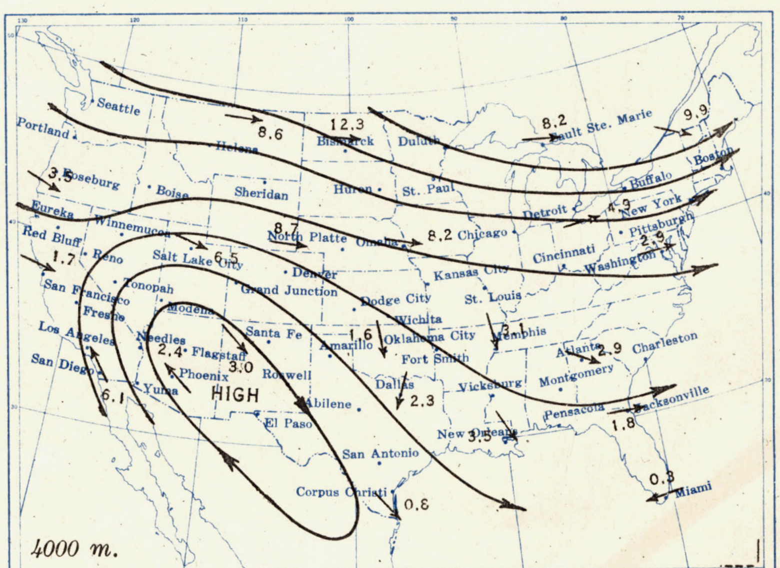
T. R. R.—9. August 1932. Temperatures above normal through the Cotton Belt and below in central and southern California.



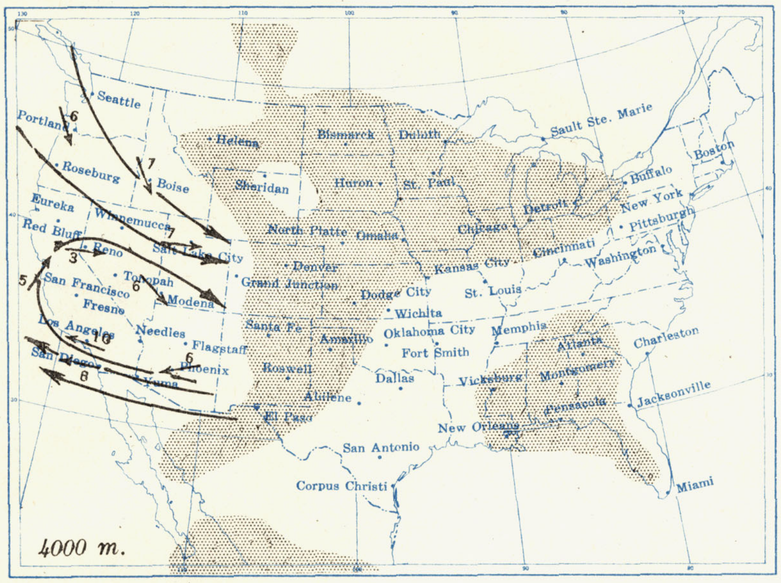
T. R. R.—10. September 1930. Temperatures decidedly above normal in west Texas and most of New Mexico.



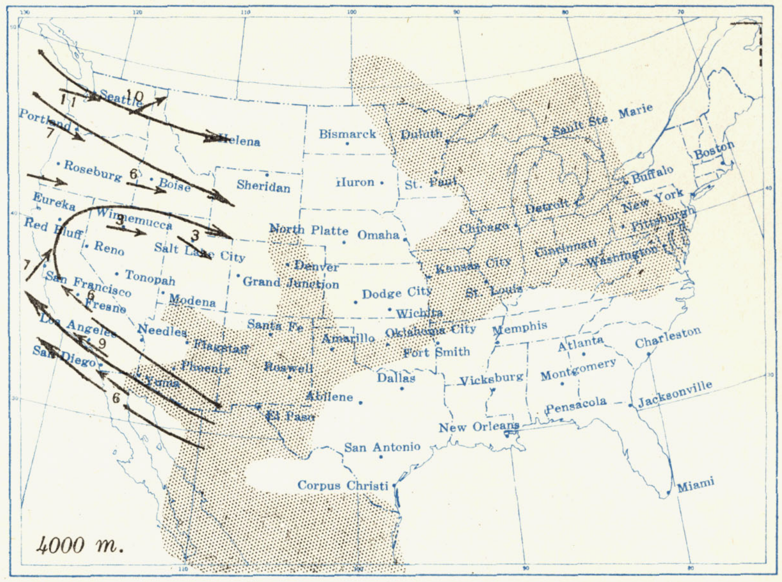
T. R. R.—11. September 1931. Temperatures much above normal throughout the Middle West and as much as 8° F. above in the lower Plains States and Oklahoma.



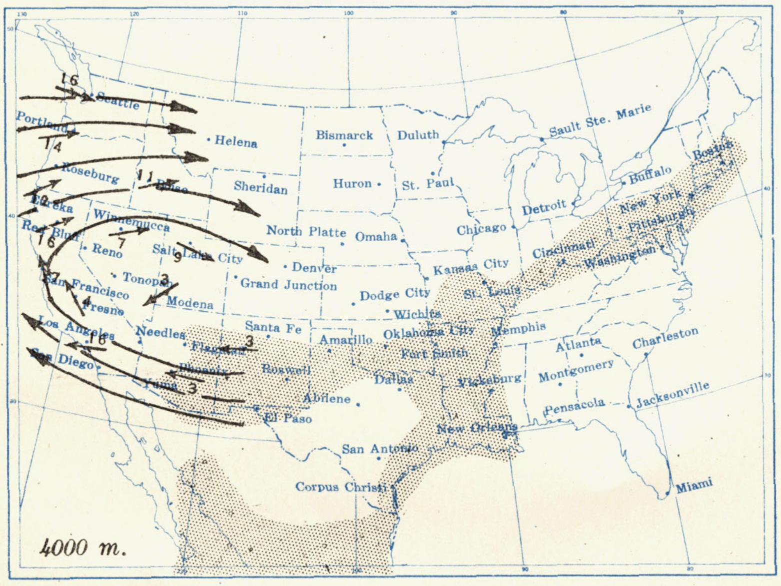
T. R. R.—12. September 1932.



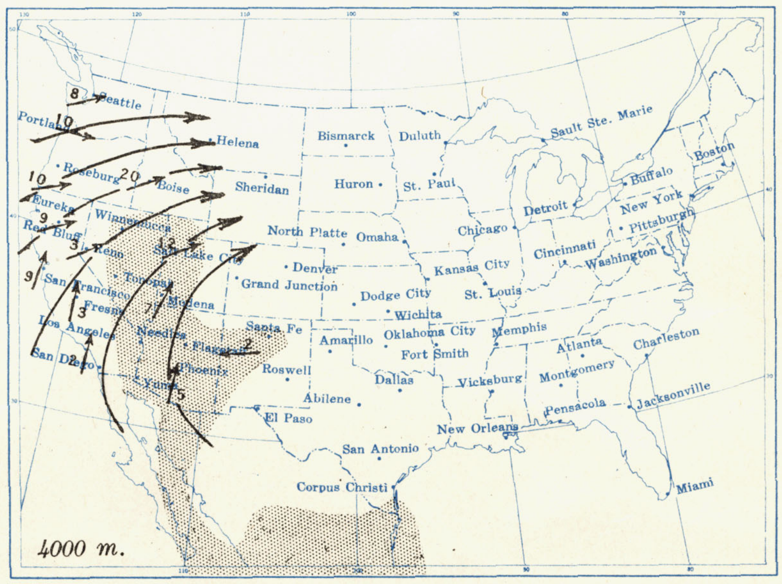
T. R. R.—13. August 1, 1931,



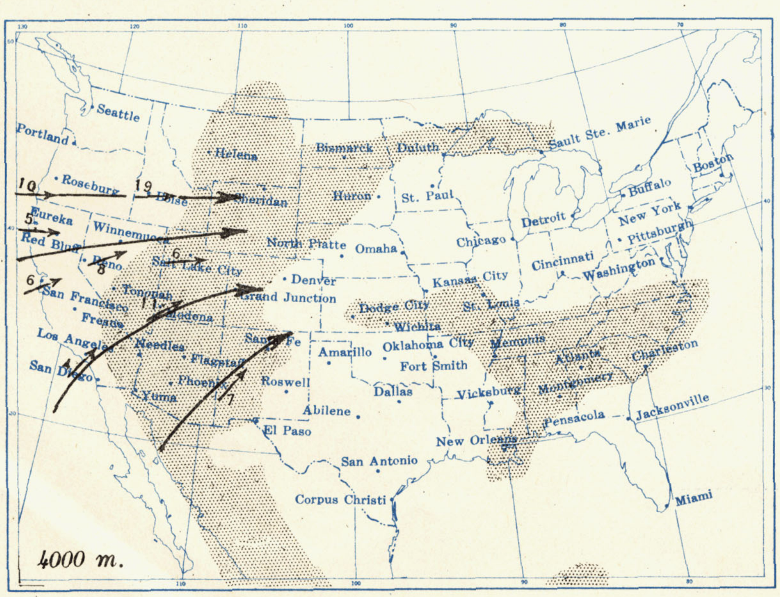
T. R. R.—14. August 2, 1931.



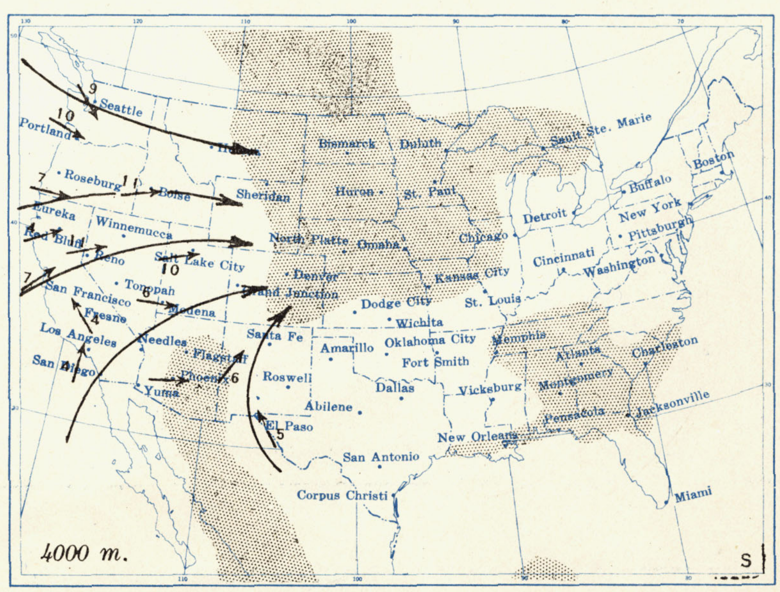
T. R. R.—15. August 3, 1931.



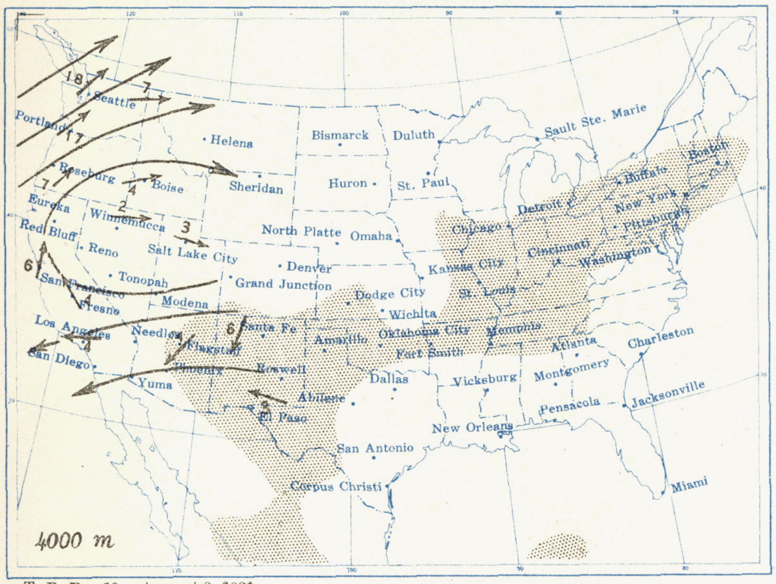
T. R. R.—16. August 4, 1931.



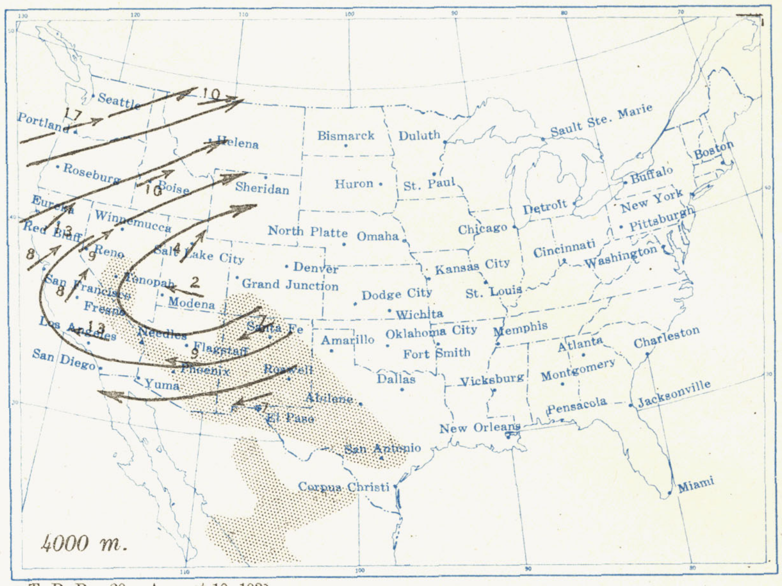
T. R. R.—17. August 5, 1931.



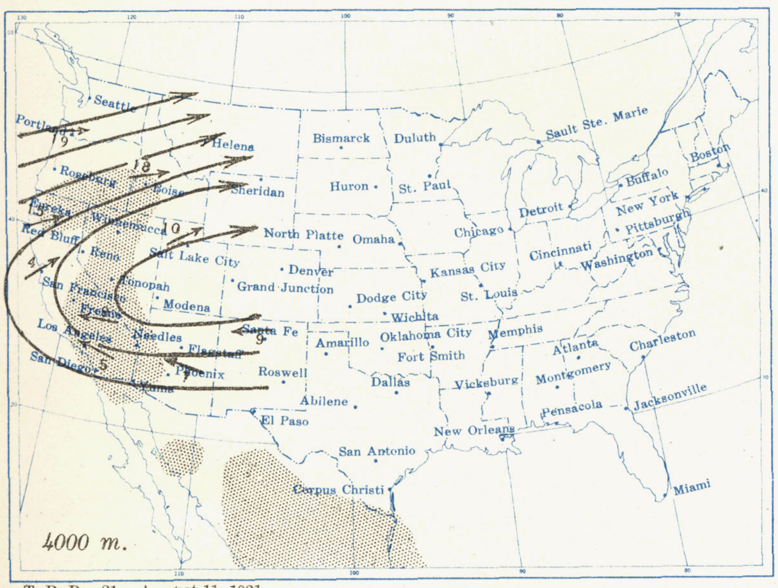
T. R. R.—18. August 7, 1931.



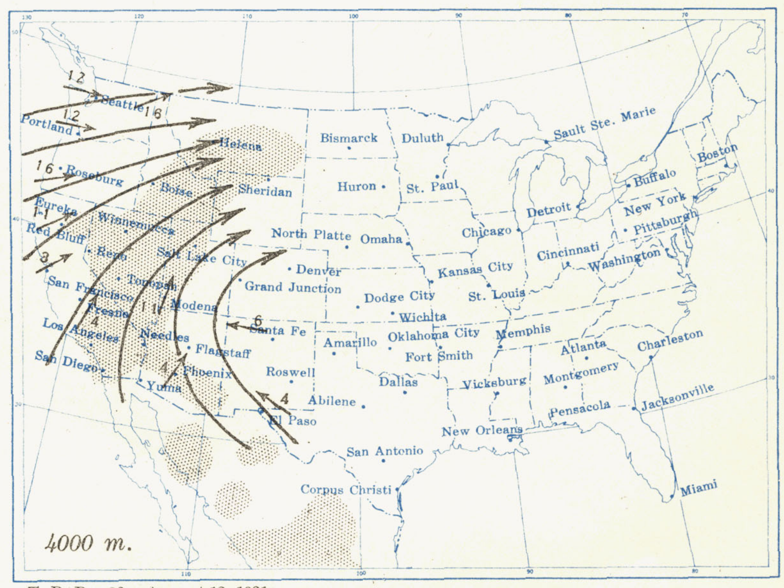
T. R. R.—19. August 9, 1931.



T. R. R.—20. August 10, 1931.



T. R. R.—21. August 11, 1931.



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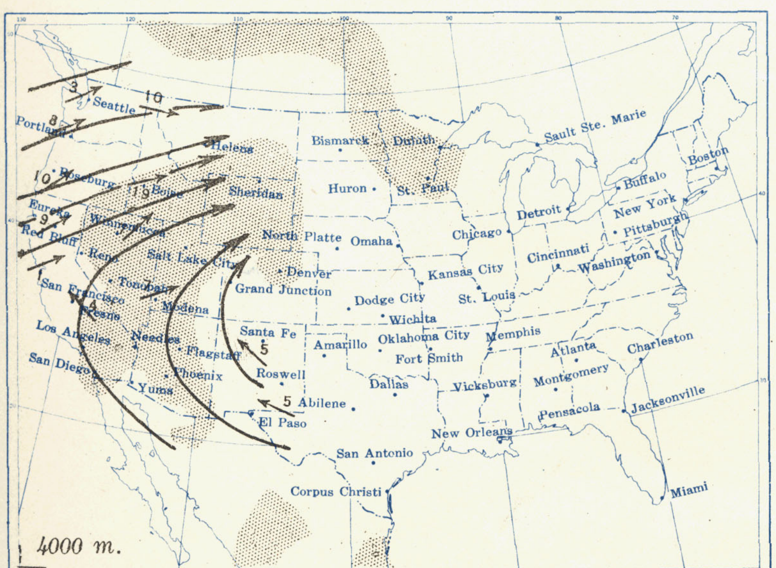

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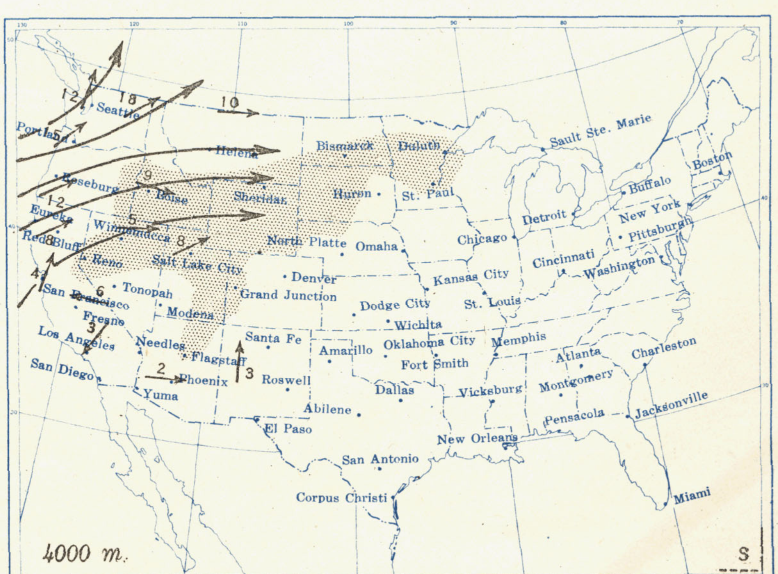
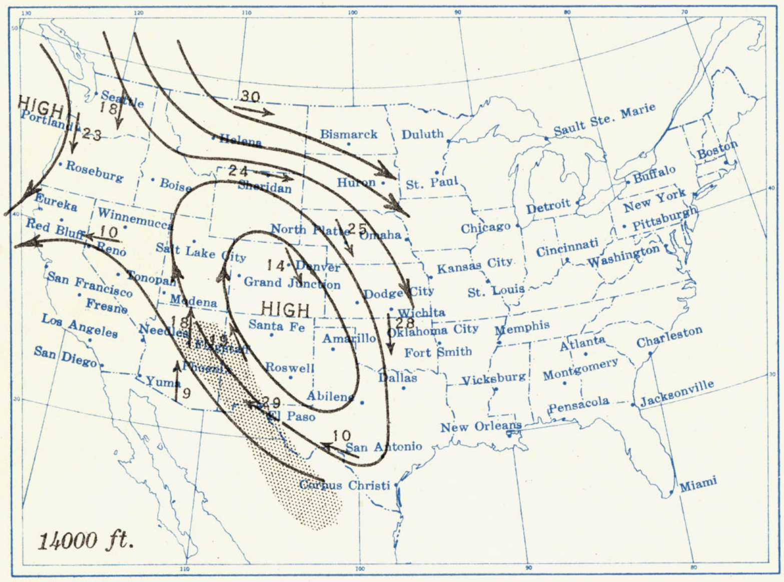
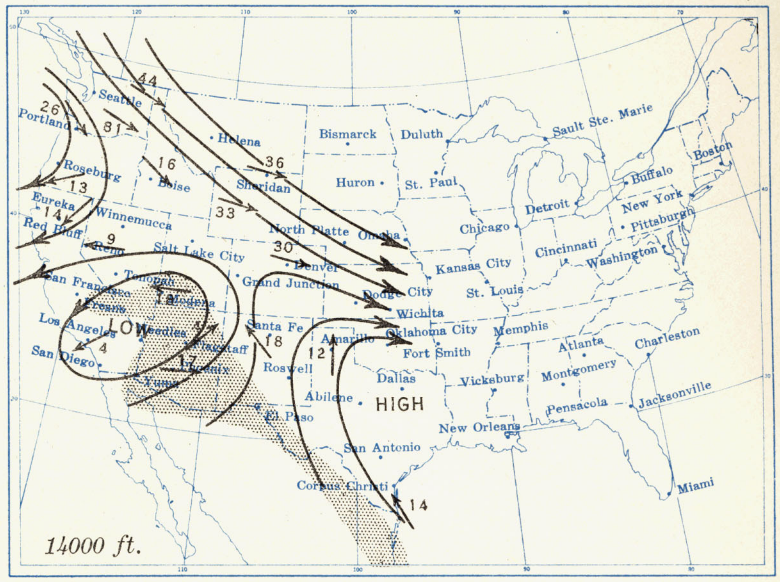


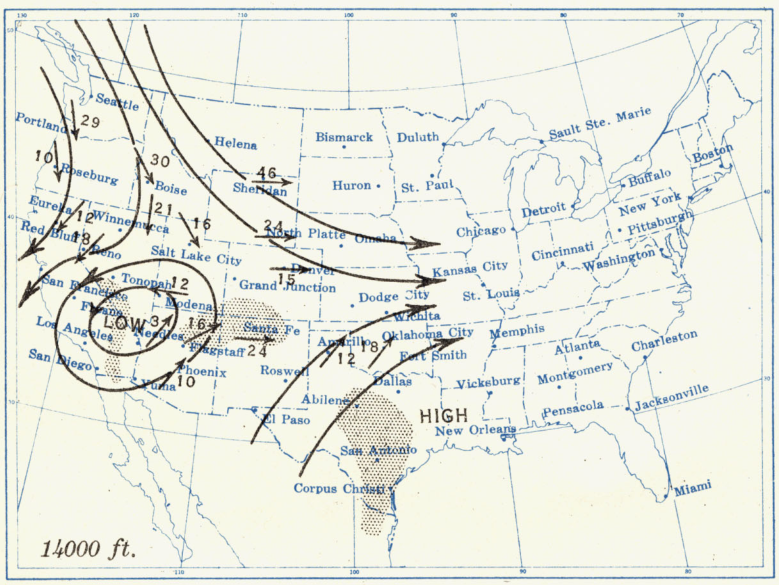
T. R. R.—24. August 14, 1931.



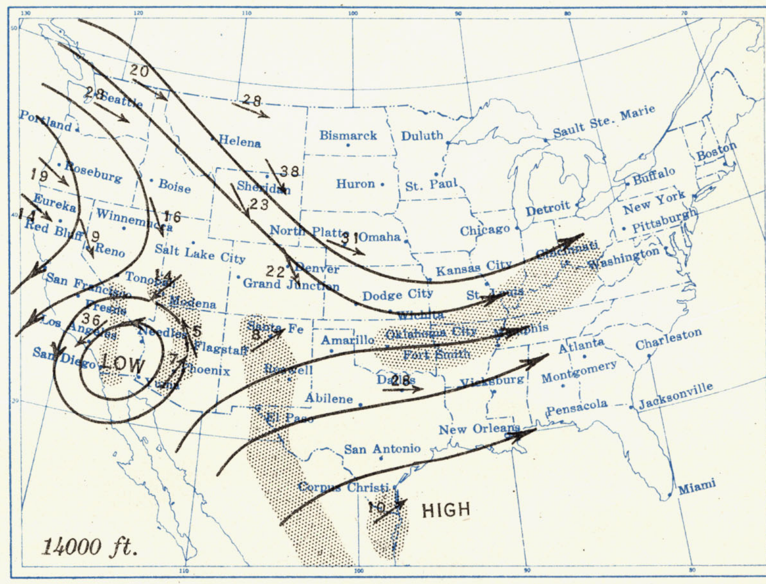
T. R. R.—25. October 9, 1933.



T. R. R.—26. October 10, 1933.



T. R. R.—27. October 11, 1933.



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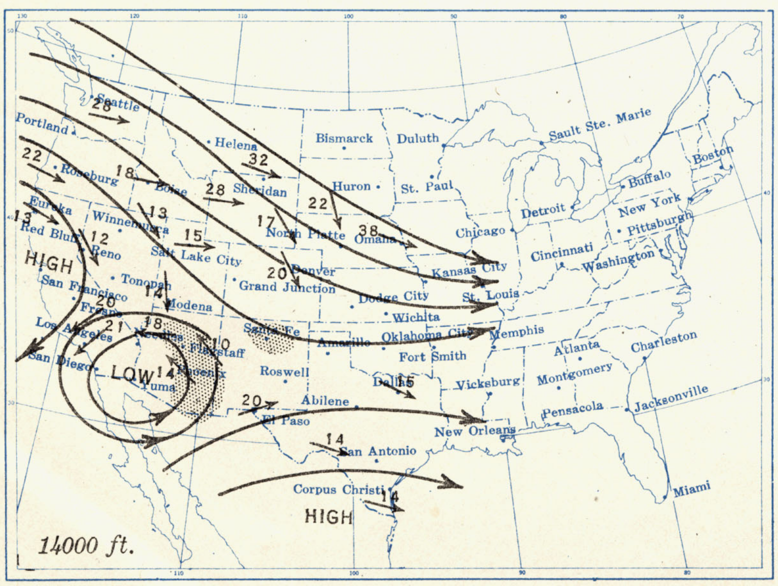

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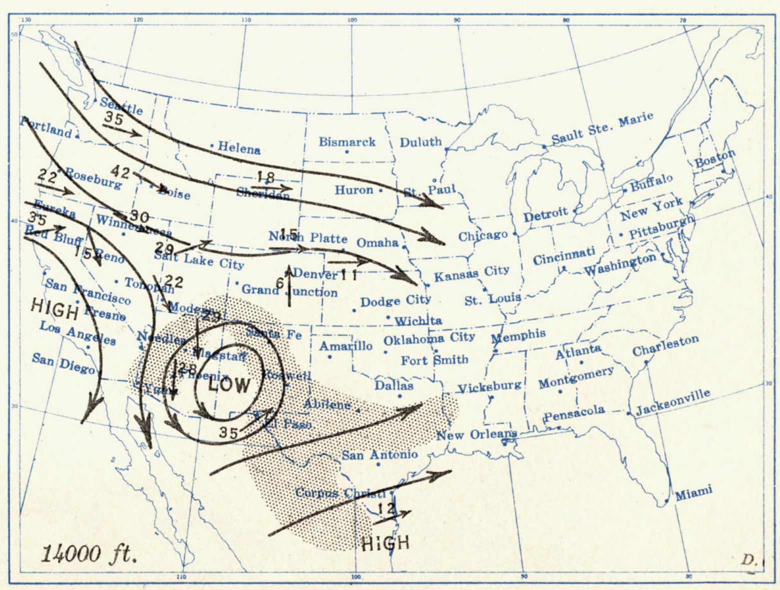

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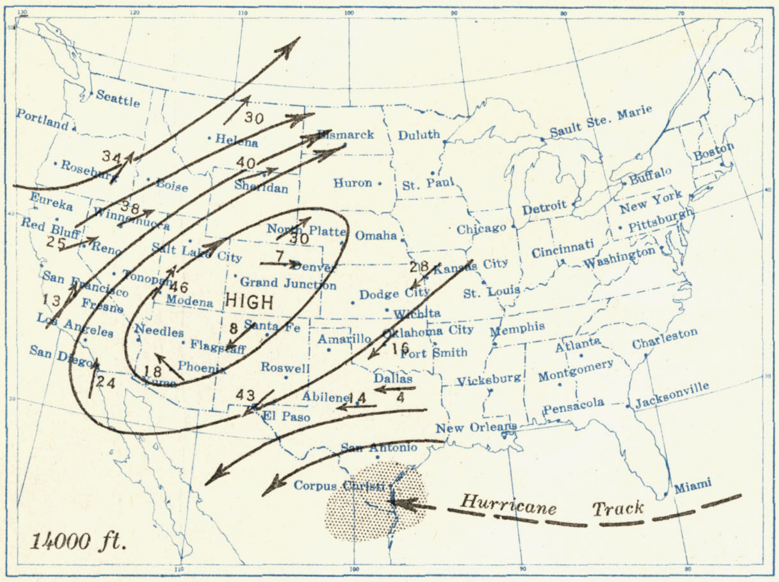

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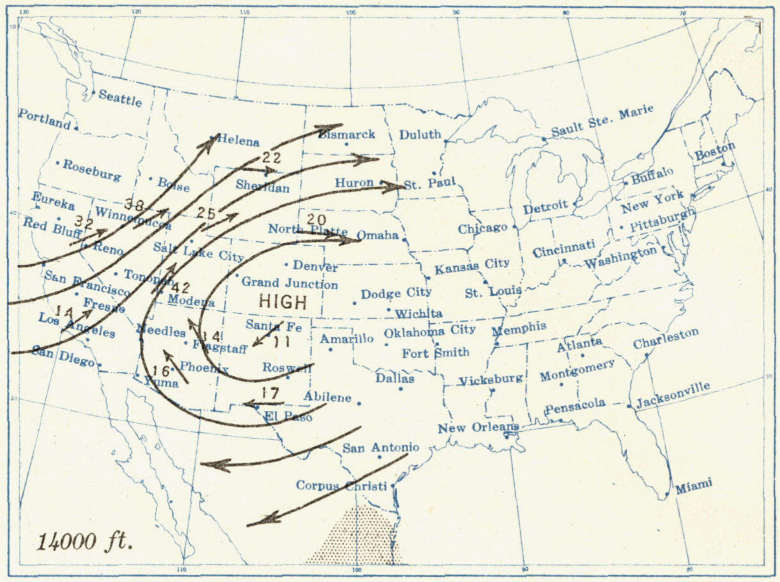

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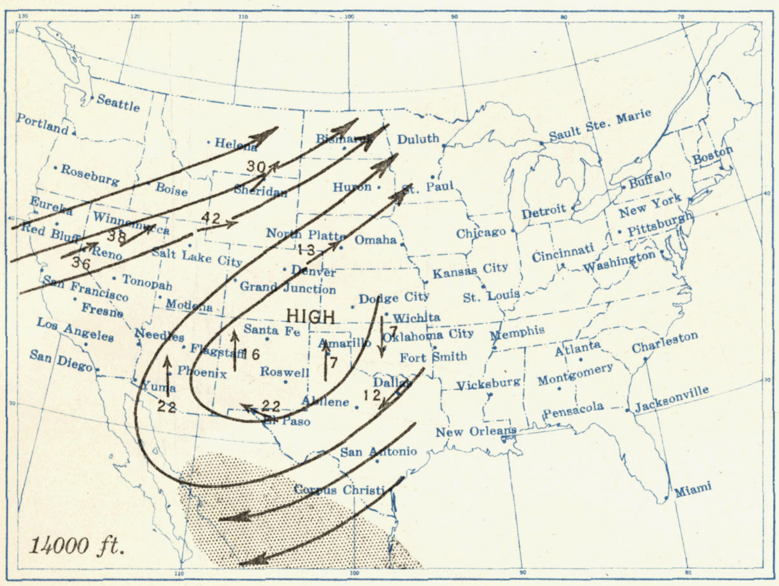

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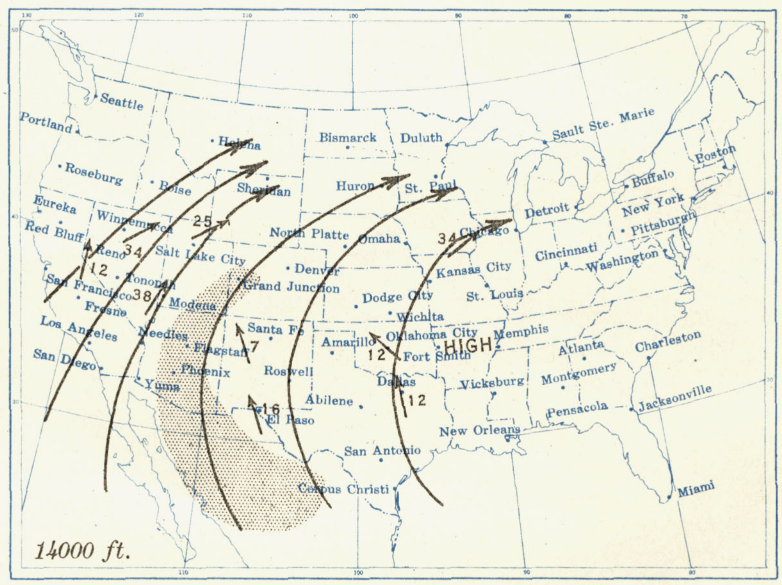

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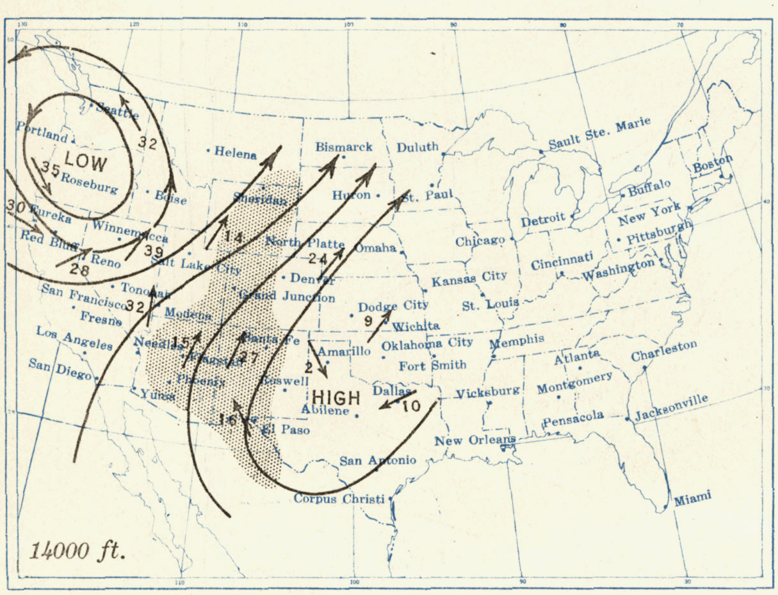

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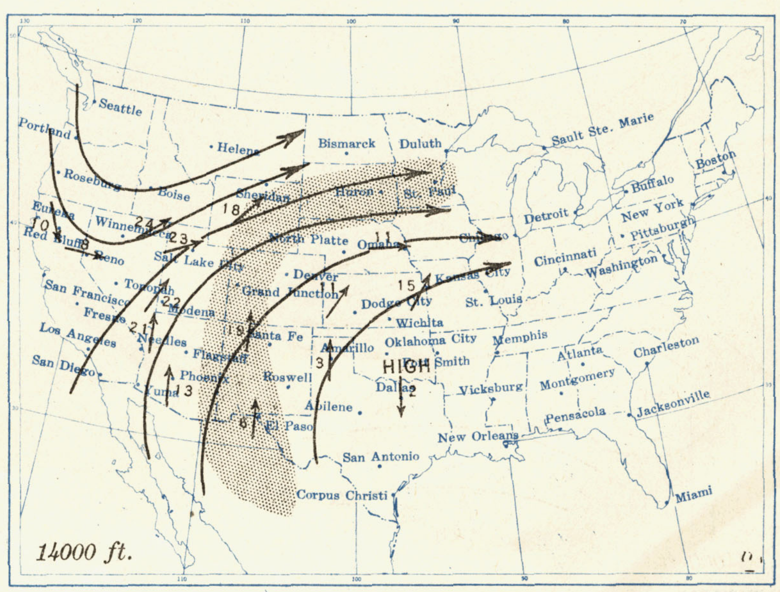

T. R. R.—36. September 10, 1933

labor the point of the relative instability of the atmospheric structure in those sectors. It is also plain that the upper portions of this mass are drifting around the anticyclone in a clockwise direction. Much of their moisture may be extracted before they reach the northern Mexican Plateau, and yet their state of conditional instability not materially altered by the journey, and hence, although the surface supplies of moisture may be scanty, surface heating is adequate to produce penetrative convection and occasional convectional rains. It is here that their clockwise turning often brings the upper winds northward over the southern Rockies, and it is then that what in Mexican terminology might be termed "chihuahua" or "Durango" rains, become in American parlance, "Arizona" rains. Moisture may or may not have been transported by them, but the essential requirement of conditional instability has been supplied by them, and so the vigorous convection initiated by the summer sun and aided by mountain slopes and ridges takes care of the rest. It is important in this connection that the student observe the sequence of rains. When rains are abundant over the Mexican plateau with the upper winds running toward the north, rains will likewise be abundant over the southern Rockies; when they cease over the Mexican plateau, they are also likely to become quite local or stop altogether over the west slope of the Rockies. Also, and of even greater import, when the anticyclone is centered west of the continental divide and there is consequently no importation of conditionally unstable air aloft, rains are practically certain to cease west of the Rockies; it is a "dry" type for the entire Southwest.

Now to return to the original question, Why is conditionally unstable air found so frequently over the Mexican plateau, and so seldom to the west of it? Why the sharp line of demarcation? One cause has been suggested, namely, the mountains fringing the western border of the Mexican plateau, down which the air crossing them in its circuit of the anticyclone must descend. Evidently this air loses nearly all its moisture in crossing this final barrier, and it also (which is more important) is warmed by descent. Being dry it retains its warmth, losing little heat by radiation thereafter, and moves northward over western Sonora and California, as an air mass of such stability that although supplies of surface moisture are abundant and surface heating the greatest in the United States, penetrative convection is prohibited and a rainless regime is assured.

Another item that may contribute to this effect is the greater steepness of the barometric slope aloft near the Pacific Ocean. In this region the contrast between oceanic chill and continental warmth is most extreme, and hence the pressure gradients in this sector of the anticyclone are quite pronounced. Conceivably there is a "sliding" of the air across the isobars in this sector which brings it to ever lower levels and consequently higher temperature in its northward journey.

This may be a fact of more importance than at first appears, as offering a clue to the occasional westward movement of the Arizona rain belt. When this event happens we see the Arizona rains transplanted to southeastern California, and the so-called "Sonora" storms in progress there. This situation is usually anticipated by east winds aloft over southern California[4] indicating clearly that conditionally unstable air from the Mexican plateau is drifting westward and introducing over the deserts and mountains of southern California the atmospheric structure which normally exists over the southern Rockies. The sources of this air and its movements can be traced by reference to upper wind reports and the progress of the rain area on the ground. The remarkable feature of this event is the fact that the air in such cases succeeds in making its transit from the Mexican plateau without being warmed by descent en route. Two circumstances may be mentioned as permissive of this possibility. One is that the east winds aloft which often precede this situation, imply a marked change in the direction of the isobars aloft. Instead of paralleling the coast they must be at some more or less acute angle to it. When parallel to it they are, as has been explained, crowded, with a consequent sliding off of the air, its descent and warming. When, on the other hand, the isobars aloft cross the coast line, as implied by easterly winds in the free air, they are not necessarily crowded, and the warming descent across the isobars is mitigated. The other contributing circumstance may be the vapor content of the air which crosses over. If its vapor content were relatively high, loss of heat by radiation might conceivably offset the effect of adiabatic warming, with the result that it would retain its conditionally unstable state after leaving the Mexican plateau and arriving over southern California. Observations supporting this view, obtained by airplane flights over San Diego, will be cited further on.

E. A. Beals in his paper on "The Semipermanent Arizona Low"[5] published before the advent of free air observations throughout the Far West, proposed the view that the barometric trough over the Far Southwest in summer ultimates occasionally in rain producing depressions which "bud off" from it and travel eastward. Their formation, however, was admittedly fortuitous, and no explanation could be offered for the development of convectional rains in the so-called trough at one time and not at another. We understand now that the depressions that seem to "bud off" from the trough are not contingent on a pressure situation implied by isobars drawn through Sir Napier Shaw's "ten thousand feet of rock", but on the temperature of the air imported aloft by the high-level anticyclone. When its temperature is low (relatively) or when the air mass is moist enough to cool by radiation as it travels, then we may expect to see rains associated with it, which travel forward with the unstable mass. The factor which determines their formation and travel, however, is not the apparent trough, but the air currents circulating aloft, which foster stable or unstable conditions according as their temperature is high or low. The phenomenon presents a vivid illustration of the second of Humphreys' three conditions by which a vertical temperature gradient necessary to convection can be

[4] Blake in his article on "Sonora Storms" (MONTHLY WEATHER REVIEW, November 1923) says: "After careful observation the writer has yet to observe a single instance of severe 'Sonora' conditions when the upper-cloud movement was other than from an easterly direction." It will be of profit to the reader to review this whole article as it describes in pleasing detail a far western weather type which baffled investigation prior to the advent of regular upper-air soundings in and around the region concerned. He will see that the term "Sonora" no more describes the origin of the summer rains and thunderstorms of southern California, than the term "Arizona rains" describes the source of like phenomena in the southern Rockies. Both are contingent on the establishment of a favorable lapse rate for penetrative convection, and this is provided not by a change in conditions below but by the introduction of suitable air aloft.

[5] MONTHLY WEATHER REVIEW, July 1922.

established, viz, "the overrunning of one layer of air by another at a temperature sufficiently lower to induce convection." [6] The quotations would be still more apposite if we substitute the word "sustain" for "induce", as convection in the cases we are considering is usually *induced* by surface heating but *sustained* to the point of condensation by the lapse rate provided by the overrunning air.

I have said that the prime necessity is either "cold" air aloft, or air that is moist enough to cool by radiation in its travel. In either event we secure the desideratum for the formation of cloud and rain, viz, instability. And I have cited Beals as pointing out that when this condition (which he associated with the summer trough) exists, active depressions sometimes ensue. That cyclonic circulation sometimes does develop is shown by data plotted on the free-air wind charts. Such circulation is never confirmed by surface observations as the rugged west-continental relief prohibits even approximate conformity to gradient wind requirements near the ground. But at levels above the disturbing element of mountain peaks and ridges the air is occasionally found to be circulating in a counterclockwise direction on the periphery of the high-level anticyclone. The fact that this phenomenon is more likely to appear in the fall than in midsummer implies that the lengthening nights of autumn may be a contributing factor. This has led E. H. Bowie, to suggest that cooling of moist air aloft by radiation from its vapor laden strata is responsible. Such cooling over a wide area would result in a subsidence or "shrinking" of the strata. To be sure this would in turn produce dynamic warming, but if radiative conditions were suitable they might offset it. The resulting local concavity in the isobarometric surfaces, Bowie further points out, might result in inflowing, counterclockwise winds aloft and the development of a cyclonic circulation at high levels. The idea is certainly ingenious, and deserves being followed up with a searching quantitative analysis.

But whatever the cause, the phenomena are undeniable. And so we see rains on the periphery of the high-level anticyclone associated at one time with a local counterclockwise system of winds and at another time with an undisturbed current turning slowly around the anticyclone in a clockwise sense. But the essential requirement in either case seems to be the importation or manufacture of conditionally unstable air aloft, after which convection initiated by surface heating and aided by mountain slopes has a free hand.

The air mass, associated with a hurricane is obviously unstable; hence it is easy to identify it by the progress of the ensuing rain over the land after the storm has broken up on the coast and all trace of a vortex has disappeared from the weather charts. Many of the rains over the Far Southwest can be directly traced to the passage of "hurricane air" around the high-level anticyclone, sometimes coming from the east Mexican coast and sometimes from the West. The Mexican broadcast of weather observations is a vital necessity in this research, and if it included upper air reports as well as surface data the assitance would be inestimably greater. A regular practice in the San Francisco office of the Weather Bureau, after the receipt of this broadcast, is to plot the Mexican rain area on the aerological chart showing upper winds at the 14,000-foot altitude, and to note the consistency of its travel with the implied general circulation of air at that level.

[6] Physics of the Air, p. 309 (2d edition).

Precepts and examples.—It may be rash to attempt the formulation of rules with so little observational experience to draw upon, and the inclusion of the term "precepts" in the topical heading may seem, to say the least, premature. Certainly, however, no objection can be raised to citing examples designed to illustrate and support assertions made in the preceding text, and it is believed that their contemplation will bring conviction where pages of argument might not suffice.

To begin with, let us take the simplest and most fundamental proposition, namely, that when the anticyclone is centered east of the Rockies conditions are favorable for the usual instability rains of the "Arizona" type, and unfavorable when it is centered west of the Rockies. In support of this it would be easy to find a great number of examples, but one that illustrates it with perfection will be found in the free air situation prevailing in September 1932. During the first 3 weeks of that month the anticyclone was centered almost continuously west of the Continental Divide, most of the time over Nevada, southern California or western Arizona. During this entire period an almost rainless régime prevailed over and west of the southern Rockies. It was a subject of remark by section directors in their weekly weather and crop reports: All Rocky Mountain stations reported a deficit of rainfall. On the 20th of this month the center of the anticyclone shifted east of the Rockies and almost simultaneously rains were reported at Tucson and El Paso, reaching Flagstaff and Santa Fe on the 21st, and running north into Utah, Colorado, and Wyoming by the 23d. The anticyclone remained east of the Rockies for the reminder of the month. The "Weather and Crop Bulletin" of September 27 showed an excess of rainfall at Amarillo, El Paso, Roswell, Santa Fe, and Flagstaff, a condition repeated the following week (except for a slight deficit at Santa Fe) and made the subject of remark by section directors, the New Mexico official reporting the week as "cloudy, cool, and rainy", and the Arizona official as characterized by "much cooler weather, with mostly light to moderate beneficial rains."

Another precept of importance is that an existing rain "area" shows a marked tendency to progress in the direction of the upper winds. Take for example the situation in August 1931. (Charts 13 to 18.) On the 1st showers and thunderstorms were general east of the Continental Divide, but the weather was rainless to the west of it. East winds were running aloft over southern Arizona and within 36 hours the Texas rain area had pushed westward over the border States as far as Yuma. On the 4th the center of the high-level anticyclone shifted to the eastward; winds over Arizona were consequently running from the south instead of from the east, and by the morning of the 5th the rain had turned northward, too, and covered all the lower Colorado Valley, eastern Nevada and western Utah, extending into the northern Rockies and the Dakotas by the 8th. During this period rains had been general over the Mexican Plateau, but on the 6th they began to cease. Within 2 days they also ceased nearly everywhere in our States west of the Continental Divide. A régime very like the one just described began again on the 9th (charts 19 to 24) with winds aloft setting in from the east over the southern border and later veering to south and southwest as the center of the anticyclone moved eastward. Rains, as before, spread westward from New Mexico, this time reaching the southern California coast, whence they ran northward with the veering wind stream aloft, covering eastern

California and Nevada by the 12th and reaching Wyoming by the 14th. On the 13th they had begun to cease in nothern Mexico, and within 3 days had practically ceased in the plateau region, California, and western Arizona.

In considering these and other examples of a progressive rain, the reader is asked to keep in view the fact that the moisture deposited as rain is not necessarily imported from sources suggested by the rain area. No such claim is made. All that is required to be imported is air of suitable temperature aloft to permit penetrative convection. With this atmospheric structure established existing supplies of surface moisture are ample to account for the attendant phenomenon of precipitation. That is why the summer rains of the desert region of southern California, on the rare occasions when they do occur, are likely to be more abundant than elsewhere, sometimes reaching cloudburst proportions. The moisture to produce them is already there in more abundance than in adjacent regions to the eastward: all that is ordinarily lacking to produce convective rains is a lapse rate permissive of ascending air.

It will be remarked that the foregoing examples also serve to confirm Blake's observation that "Sonora" rains are preceded by easterly winds at high levels. This was again confirmed during the month in review (August 1931). Winds aloft over southern California were from the east on the 25th. Then the center of the high-level anticyclone shifted east of the Rockies and on the 27th rains fell over southern California and southern Arizona, running northward into the southern plateau region by the 29th. By that date a high-level cyclone was in evidence, apparently centered near and west of the southern California coast.

By a "high-level cyclone" is meant a system of counterclockwise winds aloft, a phenomenon, as has already been said, which is not uncommon over the far western United States, and which sometimes seems to originate in upper air which has been transported into those regions by the agency of the high-level anticyclone. Such developments are not necessarily indigenous to that air, but in the warm season it is their likeliest source. The search for "fronts" in this situation is futile, and the phenomenon seems best explained by Bowie's hypothesis (already referred to), namely, a local sinking or contraction of the upper strata caused by free air cooling. The essential requirement for such cooling is, of course, a vapor mass aloft to serve in a radiative capacity, and that this may be occasionally supplied there is specific evidence. This evidence has been found in recent aerological flights made by airplane over San Diego, Calif. To cite a particular case, the period September 27 to October 15, 1933, has been selected. (Charts 25 to 30.) Prior to September 27, winds aloft over southern California had been from the west and the weather over the far southwest rainless. On the 27th winds aloft over San Diego became easterly, indicating a movement of upper air from the Mexican Plateau where rains had been in progress. Within 24 hours the dew point at 4,000 m over San Diego had risen 35° (from −1° F. to 34° F.) while the temperature had fallen 6° F. This condition of relatively high dew point continued until October 12, during which time there was an irregular decline in temperature at the same level reaching a minimum on that date of 22° F., after which the dew point fell abruptly and the temperature rose. Prior to September 28, as has been said, the weather had been rainless, but on the 28th (the day after the wind aloft had reversed direction and set in from the east) thunderstorms occurred in the mountains of southern California, continuing at intervals until October 12. On October 10, when the cooling aloft had nearly reached its maximum, a cyclonic circulation was clearly in evidence at the 14,000 foot level with the vortex over the lower Colorado Valley. This circulation persisted over that region for 4 days and then drifted eastward to the southern Rockies.

In conclusion, it is desired to cite two examples of the transportation by the high-level anticylcone of air masses associated with the development of hurricanes. In one case the hurricane was an east coast phenomenon, and in the other it formed and disappeared in the west, but in each case the air mass in which the hurricane had flourished moved in channels evidently determined by the anticyclone.

The first of these (charts 31 to 36) dissipated near Brownsville, Tex., on September 4, 1933, after having crossed the Gulf of Mexico. At this time the anticyclone was centered over the southern Rockies, and winds aloft over Texas were from the east-northeast. Presumably over northern Mexico they were substantially the same. On the 5th the rain was evident only over the region where the hurricane had disappeared, but by the 6th it had crossed Mexico toward the southwest, and torrential rain had fallen at Monterey. On the 7th it had expanded and spread northward on the west coast as far as Culiacan, with very heavy rain recorded at Mazatlan. On the 8th with the anticyclone transferred to the Gulf States and winds aloft running toward the north everywhere west of the continental divide, the rain began to spread northward, covering eastern Arizona and reaching Grand Junction, Colo. On the 9th with south winds still running aloft, the rain continued northward into Wyoming, with general rains prevailing along the west slopes of the Rockies, which were extended by veering winds aloft into the Plains States the day after.

The west coast example (charts omitted) is the hurricane of September 1932 which appeared off Manzanillo on the 27th, was charted at sea on two succeeding dates as it moved northward, and finally disappeared in the lower Gulf of California on the 29th. The air in which this disturbance originated has been associated by competent meteorologists with the torrential rains which occurred simultaneously in the Tehachapi Mountains of southern California, washing out railroads and highways, and involving property damage estimated at over a million dollars.[7] The high-level anticyclone appeared to be somewhere over the Gulf States, as winds at high levels were running from the south over the Mexican border States. On September 29, the last day on which the hurricane appeared in the form of a surface vortex on the weather chart, rains and thunderstorms were reported over nearly all of Mexico except regions bordering on the Gulf of California (where only a few reporting stations are located) and also over nearly all of New Mexico, Arizona, and southern California. Obviously the hurricane was not responsible for all these events; but the atmospheric structure which fostered the formation of one also fostered the formation of the others, and the travel of this structure was necessarily from south to north in the path of the high-level winds. On the 30th there was evidence of a high-level cyclone over southern California, but winds aloft over Texas and New Mexico had veered toward the east. Hence while rains continued in southern California and Arizona, the Mexican rain area pushed northeastward across New Mexico into the Texas Panhandle and Oklahoma.

[7] Destructive Rains in the Tehachapi Mountains, Kern County, Calif. Malcolm Sprague. Climatological Data, California Section, October 1932.